Distribution and Characteristics of Dikes in the Southeast Part of the Koolau Range, Oahu[1]

GORDON E. BIGELOW[2]

ABSTRACT: Exposed dikes and sills trending southwest and roughly perpendicular to the primary Koolau rift zone in the Waialae-Palolo area of Oahu are hypersthene-bearing tholeiitic rocks, intrusive equivalents of the Koolau Series basalt flows. No Honolulu Series intrusives were located along a line joining Kaau Crater, Mauumae, Kaimuki, and Diamond Head, a secondary rift of the Koolau volcano. Mineralogy of the Koolau intrusives displays a striking chemical and morphological constancy. Feldspar crystals in these rocks show antipathy to ore inclusions. Cumuloporphyritic texture is strongly developed and may be related to flow patterns evident in groundmass minerals.

INTRUSIVE BODIES in the leeward slope of the Koolau Range, Oahu, outcrop along trends closely parallel to the inferred secondary rift zones of Honolulu Series volcanics (Wentworth and Jones, 1940:981). The Kaau rift, subject of this study, was held by Winchell (1947:19) to be an underdeveloped primary south rift of the Koolau volcano (Fig. 1). Four distinct Honolulu Series vents occur aligned S 25°W from Kaau Crater through Mauumae, Kaimuki, and Diamond Head. Other sites on windward Oahu suggest continuation of the Kaau rift northeastward.

Though conspicuous in topographic expression, the Honolulu Series rifts do not seem to contain substantial intrusive bodies. A Bouguer gravity anomaly map of Oahu (Strange, Machesky, and Woollard, 1965:351) clearly suggests concentration of high density material along the primary northwest-trending Koolau rift. This anomaly has been interpreted as a volcanic plug (Adams and Furumoto, 1965: 296). The Koko, Kaau, Tantalus, and Haiku rifts (Winchell, 1947:19–20) of the Honolulu Series show no corresponding gravity effects. The feeders of the Honolulu Series eruptions thus were probably simple dike fissures.

Dikes in the Palolo and Waialaenui valleys consistently strike southwestward along the Kaau rift or southeastward parallel to the primary rift of the Koolau volcano (Wentworth and Jones, 1940:981–982). The exploitation of the southwestward zone of crustal weakness in the Koolau volcano by Honolulu Series eruptives suggested that some of the intrusives now exposed in the deeply incised Palolo and Waialaenui valleys might belong to the Honolulu Series.

This study is a petrographic examination of 26 intrusives sampled along the trend of the Kaau rift. Maps prepared by Stearns (1939) and by Wentworth and Jones (1940) indicate approximately 100 intrusive bodies located in this area. Continuous exposures of individual intrusive bodies seldom exceed 20 feet, however, and are often less than 10 feet. The marked parallelism of these outcrops suggests that many dikes mapped separately are actually continuous under the mantle of soil and vegetation.

FIELD WORK

Dikes were mapped and sampled during the summer of 1967 in the Pukele (west) and Waiomao (east) branches of the Palolo Valley and in the Waialaenui Valley. Locations were established by Brunton compass, using utility poles and power lines as reference. Dikes were sampled at centers and margins. For larger intrusives several samples were taken at intervals inward from margins.

Most of the intrusive outcrops found in this study were in or near streams. The three ridges adjoining the Palolo and Waialaenui valleys were searched, but soil and vegetation cover all

[1] Manuscript received April 14, 1969.
[2] Chaminade College, Honolulu, Hawaii.

except the expansive 'buds' (Wentworth and Jones, 1940:989) which appear on the eastern slope of the Waialaenui Valley. In most cases it was impossible to determine whether exposures located in this study correspond to those mapped by Stearns and by Wentworth and Jones. The vicinity of Kaau Crater was searched with particular thoroughness. Its proximity to the primary Koolau rift and the abundance of intrusives already mapped on its eastern flank made it a promising site for exposures. Maumae and Kaimuki were examined, an east-west freeway cut providing fresh exposure through the latter. The rim, crater, and flanks of Diamond Head were also searched. Abundant dike exposures were found near Kaau Crater; but none appeared near the other eruptive sites mentioned, despite reports by Hitchcock (1900: 45), Wentworth (1926:44–45), and Stearns (1939:41) of substantial Honolulu Series dikes on the southeast side of Diamond Head. Much of this area has now been enclosed by retaining walls and other construction.

FIELD STRUCTURES AND RELATIONS

The deep dissection of the southern slope of the Koolau shield volcano has formed a series of steep-sided, southwest-trending ridges with intervening valleys concentrating drainage abruptly in the uplands (Fig. 2). The shield consists of lava flows, usually 4 to 12 feet in thickness, dipping gently southward in the area studied and showing little evidence of weathering between flows. The texture varies from coarsely vesicular and clinkery material on the tops and bottoms of flows to dense, vertically jointed blocks in the centers. Lava tubes are common, but are generally small and only a few feet in length. None was found filled by intrusion, although such fillings have been observed elsewhere in the Koolau Range.

FIG. 1. Aerial view southward across Kaau Crater (*center*) toward Diamond Head (*upper right*). The low shield of Kaimuki is not distinguishable at this angle. (Photograph by A. T. Abbott.)

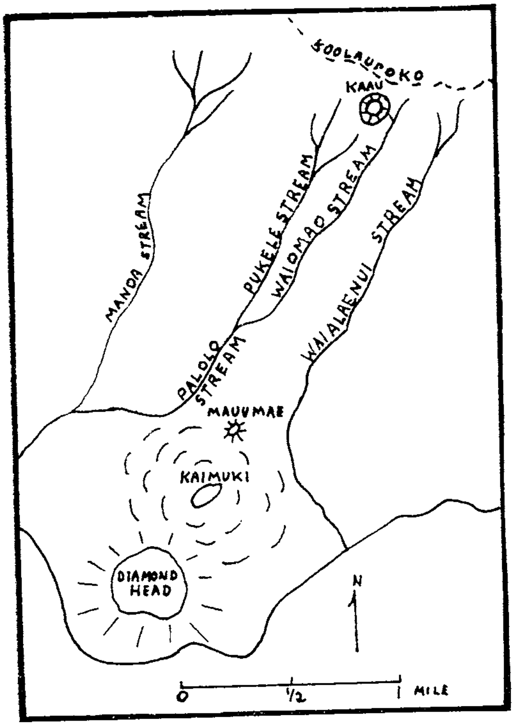

FIG. 2. Eruptive features and main streams of the Waialae-Palolo area, southeastern Oahu.

Dikes commonly intersect the flows at high angles, near the normal to the flow plane. Of the intrusives observed, 13 dip less than 65°, however, and 5 were below 35°. Dike trends are typically near S 45–55°W and S 40–50°E, but vary widely. Limited exposures prevented precise determination of the dip of many dikes.

The relatively unconsolidated clinker between flows was not observed to offer a plane of weakness to the intrusive bodies. Thus the interpretation of apparently conformable intrusives as sills required extreme caution in following the contact, and often remained in doubt. The dips of five intrusives tentatively identified as sills ranged from 5° to 14°. Wider samplings by Wentworth and Jones (1940:981) and Stearns (1939) remain the basis for judgments on the attitudes of leeward Koolau intrusives.

The dikes studied ranged in thickness from glassy stringers a fraction of an inch across and lensing out completely, to a dense, massively jointed holocrystalline body 78 inches wide. The 'bud' sampled is an intrusive body with concentric platy jointing, several tens of feet across and of indeterminate height (26 feet exposed with bottom apparently converging downward). These buds have been described in detail elsewhere (Wentworth and Jones, 1940:988–990).

The Palolo Quarry intrusive is not included in the scope of this study, although it is within the area here described. Detailed studies appear elsewhere of its structure (Wentworth and Jones, 1940:986–988) and its petrogenesis (Kuno, et al., 1957:181–187).

LABORATORY PROCEDURE

Five thin sections were prepared from samplings of each intrusive. These were petrographically described and nine modal analyses (1000 points each) were completed, including two on different thin sections of the same dike as a measure of sampling error. Composition of phenocryst feldspar, ferromagnesian minerals, and interstitial glass was determined by oil immersion of powdered samples. Matrix feldspar composition was determined by maximum extinction angles of microlites.

Textural descriptions are as defined by Johannsen (1931) and Williams, Turner, and Gilbert (1954). Mineral data follow Heinrich (1965) and Winchell and Winchell (1937).

Measurements of optic axial angle (2V) were by Tobi's method (Bloss, 1961:205) for clinopyroxenes, Wright's method (Bloss, 1961:203) for orthopyroxene and Kamb's method (Bloss, 1961:179–180) for olivine. Individual values of these readings commonly vary ± 3–5 percent, and so ranges based on a probability distribution of several hundred readings have been reported.

PETROGRAPHY

The dikes and sills of this area are typically porphyritic with a fine-grained, hypocrystalline matrix, commonly intersertal in the coarser centers to hyaloophitic at the chilled margins.

Phenocrysts

Phenocrysts of olivine, orthopyroxene, and plagioclase constitute 1 to 40 percent of the rock in widely varying combinations.

OLIVINE: Olivine comprises 1 to 4 percent of the dikes and sills, although it sometimes was not observed in entire sections. Some larger intrusives in this area contain 20 percent olivine by volume. Crystals range in size from matrix grains 0.02 to 0.1 mm across to tabular phenocrysts 3.0 mm long. Individuals 1.0 to 1.5 mm long are common. Y-indices of 1.686 to 1.692 indicate compositions in the range Fo_{80-85}.

Iddingsite rims are common, but they are generally not well developed and frequently do not appear in an entire section. They manifest no relation to crystal size. In the Waialaenui bud, iddingsite formation was more advanced, sometimes consuming entire large olivine phenocrysts. Hematite flakes sometimes appear in these rims in parallel arrangement or each with its long dimension normal to the olivine margins. Parts of these rims showing variable coloration have indices considerably below olivine, perhaps an alteration product of the olivine (serpentine?). Overgrowths of pyroxene are rare and were not observed to accompany iddingsite. Second generations of late-growth olivine beyond iddingsite rims do not occur.

Some olivine phenocrysts are euhedral, especially in dike margins, but more commonly, rounded or deeply embayed crystals contain invasions of late-formed matrix minerals and glass. Infrequent cores of olivine in orthopyroxene phenocrysts have been almost completely resorbed. Long, very thin survivals of larger olivine phenocrysts are common.

ORTHOPYROXENE: Orthopyroxene shares with olivine the early phenocryst role (Cross, 1915: 19). Sizes range from 0.3 mm to 1.5 mm, apparently not extending into the groundmass size. $2V_x$ range of 80° to 85° and Z-indices of 1.685 to 1.690 indicate compositions of En_{79-84}.

Orthopyroxene phenocrysts comprise 0.2 to 6.5 percent of the volume of dikes and sills, usually exceeding the olivine fraction. These orthopyroxenes are typically clear and optically homogeneous. Inclusions of magnetite are not common. Exsolution lamellae were not observed. In thin sections 0.04 to 0.05 mm thick distinct pleochroism was noted, from brownish pink in the fast direction to bluish green in the slow direction. Orthopyroxene phenocrysts also are conspicuously rounded by resorption, but are only occasionally embayed. They frequently form cumuloporphyritic clusters alone or with feldspar phenocrysts of comparable size, often in subradial arrangement. Some stand distinctly apart from such clots, however, as do all of those with olivine cores. Olivine phenocrysts do not enter the glomerocrysts.

Orthopyroxene phenocrysts with clinopyroxene jackets rarely occur. This is the only association of clinopyroxene with the phenocryst phase, and these thin rims undoubtedly formed during the period of groundmass crystallization.

FELDSPAR: Phenocrysts of plagioclase feldspar are evident in most of the intrusive bodies examined. Individuals 1.3 to 1.5 mm long are not unusual in the cumuloporphyry. Y-indices of 1.560 to 1.567 indicate compositions An_{55-68} with the most frequent range 1.562 to 1.563 (An_{58-62}) corresponding to an intermediate labradorite. Larger phenocrysts show normal zoning in a thin outer rim. Carlsbad and pericline twinning are common, whereas albite twins are infrequently and poorly developed. Phenocryst size grades continuously into the groundmass laths. Total feldspar comprises 32 to 50 percent by volume in these rocks.

Groundmass

The groundmass consists essentially of a network of plagioclase laths with interstitial clinopyroxene crystals and glass containing included ores.

CLINOPYROXENES: Augite with $2V_z$ of 57° to 62°, pigeonite with $2V_z$ of 13° to 27° and 'subcalcic augite' (Kuno and Nagashima, 1952: 1000) with $2V_z$ of 31° to 37° have been identified as grains 0.005 to 0.15 mm across, but individuals with measurable optical properties are rare. Grains of clinopyroxene are characteristically pale brown, anhedral, and interstitial to the feldspars. Clinopyroxenes constitute 29 to 39 percent of the volume. Because they are so small and inclusion-ridden and do not manifest definable linear properties, composition of the clinopyroxenes remains in doubt.

The most useful data were obtained by choosing crystals with highest apparent birefringence and determining maximum indices in oil immersion. This procedure yielded maximum slow direction refractive index values of 1.706 to 1.723. Without basis to determine calcium content, these data are not sufficient to establish the magnesium-to-iron ratio. Judgments cannot be made, therefore, as to the proportions of pigeonite, augite, and possible pyroxenes of intermediate compositions in these rocks.

FELDSPAR: Any effort to distinguish phenocryst from matrix feldspar would have been arbitrary with the data available. The continuous gradation in feldspar crystal size suggests continuous separation of feldspar as these rocks formed. Extinction angles of groundmass microlites (method described in Heinrich, 1965: 362–364) indicate compositions of An_{56-65}.

OTHER CONSTITUENTS: Angular interstices in the groundmass are filled by amber to dark brown tachylite with index from 1.576 to 1.588, indicating compositions of 49 to 51 percent silica (George, 1924:365). In the chilled margins this glass sometimes exceeds 80 percent of the bulk volume. Glass comprises 6 to 12 percent of the total volume of the dikes.

Minute dust and skeletal crystals of magnetite are abundant in interstitial glass and matrix pyroxene, often rendering these hosts virtually opaque. Subordinate ilmenite may usually be identified. The larger olivine and orthopyroxene phenocrysts contain few or no ore inclusions. Smaller (presumably later-formed) individuals in the same section include an increasing proportion of these ores. There is a conspicuous absence of ore inclusions in feldspars. Even the microlites, whose growth may be marginally impaired by preexisting magnetite grains, stand out boldly in the groundmass between pyroxene and tachylite areas overrun by abundant octahedrons of magnetite and flakes of ilmenite.

The largest magnetite grains occur in the Waialaenui bud, where they reach 0.4 mm. In typical dike rocks ore grains seldom exceed 0.1 mm across. Ores make up 8 to 17 percent of the volume of these rocks, the most common counts being in the 11 to 14 percent range. Ore content may increase with elevation in these intrusives (Table 1). Further modal counts would be required to confirm this. Acicular apatite inclusions usually are recognizable in larger feldspar phenocrysts, especially in the Waialaenui bud. Apatite never exceeds 1 percent modal volume.

Hematite occurs as minute red and black flakes along occasional joint fractures where minor alteration has taken place. It also appears as oriented inclusions in iddingsite rims on olivine phenocrysts. These inclusions are elongate flakes or shreds, black in reflected light. Total hematite exceeds 1 percent of the rock volume only in weathered material.

Traces of alteration products, mostly of low birefringence or isotropic and with indices 1.48 to 1.55, occur in vesicles and along infrequent fractures and joint planes. These occurrences are too small for critical determinations. Fibrous development often suggests zeolites or chalcedony. Bright red and green patches and strips are probably palagonatized glass.

Vesicles comprise 1 to 10 percent of the total bulk, but may be entirely absent from denser portions. Most are consistently circular in outline.

TABLE 1

MAGNETITE-ILMENITE CONTENT OF KAAU RIFT INTRUSIVES

SAMPLE NO.	ELEVATION (feet)	ORE (modal %)	DESCRIPTION
26	320 (±10)	7.8 (±0.2)	Dense inner part of Waialaenui bud
24	560	7.7	Pegmatite from Palolo Quarry intrusive
10	830	11.3	48″–57″ dike on Waialae stream
3	920	9.1	18″–26″ dike on Waiomao stream
21	1070	11.6	26″–35″ sill (?) on Waialae stream
7	1200	12.1	36″–78″ dike on Waiomao stream
19	1480	17.1	16″–20″ dike on Kaau outlet stream
17a	1500	14.5	14″–16″ dike on Kaau outlet stream
17b	1500	14.6	Same dike as 17a

COMMENTARY

Source Magma

All intrusives sampled in this study are tholeiitic. The dikes and sills are tholeiitic basalts in the sense defined by Macdonald and Katsura (1964:89). Olivine is consistently less than 5 percent of the bulk. This is in contrast to the more olivine-rich rocks of the Honolulu Series. No occurrences of nepheline, melilite, or augite phenocrysts, diagnostic of Honolulu Series mineralogy, were found.

Marginal glass in one dike containing only minor olivine as the crystalline phase has index 1.576, indicating about 51 percent silica (George, 1924:365), which includes slight silica enrichment resulting from separation of olivine. Another dike has traces of olivine and approximately 5 percent hypersthene in a glass basis. The index of the glass is 1.588, indicating about 49 percent silica. Glassy margins of these intrusives had refractive indices consistently below 1.59, or more than 48 percent silica according to the George curve.

Numerous analyses of Koolau basalts have shown silica contents of 48 to 52 percent (Wentworth and Winchell, 1947:71). Honolulu Series rocks range from 36 percent to 45 percent silica (Winchell, 1947:30).

The petrography of the intrusives studied here closely resembles descriptions of Koolau extrusives given by other authors (Cross, 1915: 18–20; Stearns and Vaksvik, 1935:93; Wentworth and Winchell, 1947:67–70). The greater vesiculation of the latter may be attributed to the effects of extrusion.

Aside from structural relations of material in place, dike rocks are distinguished from flow fragments in the field largely by the platy or splintery jointing and lack of conspicuous vesiculation in dike material. As previously noted, iddingsite rims are never succeeded by fresh olivine growth in the intrusives observed. Second generation olivine growth is common among Koolau extrusives (Wentworth and Winchell, 1947:65) and Honolulu Series rocks (Winchell, 1947:24).

No new chemical analyses are presented here, but the petrographic evidence points to chemical equivalence between these intrusives and the flows enclosing them. There is negligible alteration of the country rock adjacent to intrusives. Only a slight baked band appears, which is often difficult to distinguish. No metasomatic effects were observed.

Paragenesis

Olivine crystallized first in these rocks, usually reacted with the melt, and was slightly altered to iddingsite, probably during concentration or upward migration of volatiles. Orthopyroxene and feldspar followed olivine after a considerable interval. In several dikes olivine phenocrysts, alone in glass at dike margins, were well developed. In some margins these phenocrysts were sharply euhedral, indicating that resorption had not yet begun. In other dikes resorption was already well advanced in these solitary phenocrysts.

The complicated interactions of feldspar and orthopyroxene cannot be generalized. A few intrusives show unequivocal precedence of one to the other, but contemporaneous growth is the rule. Minor ore inclusions occasionally appear in orthopyroxenes, but they were not observed in the feldspars. This might suggest earlier crystallization of the feldspar; but the feldspar-magnetite antipathy persists even to the fine matrix material. It apparently is not a reliable criterion of crystallization sequence.

Orthorhombic pyroxene could not be identified in crystals less than 0.2 mm across, and the limit usually is nearer 0.3 mm. Hypersthene crystallization apparently ceased before the groundmass period. Resorption suggests an interval during which orthopyroxenes were not in equilibrium with the melt. Such resorbed crystals often present their rounded surfaces to intimate contact with feldspar in glomerocrysts, interfering with growth of the latter sufficiently to indicate that resorption began, at least, substantially before the groundmass stage.

Feldspar phenocrysts grade imperceptibly into fine-grained microlites, showing continuous separation to a sharp boundary with interstitial glass. Smaller feldspar laths commonly, though not invariably, form subparallel flow patterns around glomerocrysts and other phenocrysts (Fig. 3). This may roughly distinguish intratelluric from matrix feldspar crystallization.

A small quantity of ore crystallization may actually precede olivine formation in most of

FIG. 3. Flow pattern of matrix laths near a glomerocryst composed predominantly of hypersthene. Vesicle in upper center is 0.5 mm in diameter.

these intrusives, thus being the first solid phase formed. Octahedrons of magnetite and plates of ilmenite occur scantily in the mafic phenocrysts of dikes and sills. Most of the ore-mineral crystallization belongs to the groundmass phase. In hyaloophitic chilled borders a few magnetite and ilmenite inclusions appear in olivine, but ores in the marginal glass were beyond the resolving power of the microscope. With more gradual cooling, skeletal magnetite crystals grew abundantly in and across matrix pyroxene and glass. The fine dust in tachylite indicates separation of the ore minerals to the very end of the liquid phase.

A gap is usually evident in the sizes of pyroxenes between smallest hypersthene and largest clinopyroxene. This probably represents a considerable interval of time, but it also reflects the change in conditions between magma chamber or feeder and the ultimate site of emplacement. Clinopyroxene shells on euhedral orthopyroxene phenocrysts rarely document a more intimate succession.

Optical homogeneity, and particularly the absence of exsolution lamellae, suggest that orthopyroxene in these intrusions did not develop by inversion of earlier-formed clinopyroxene. Occasional olivine cores in orthopyroxene phenocrysts indicate formation of the latter as reaction rims.

Volume abundances of clinopyroxene and orthopyroxene seem to be in crude inverse relation (Fig. 4). Perhaps early formation of orthopyroxene phenocrysts reflects lower temperature of initial crystallization, shortening the interval between beginning clinopyroxene separation and the ultimate freezing to glass. The substantial proportion of pigeonite observed in matrix material results from quenching of the melt, which prevents its inversion to orthopyroxene.

The clinopyroxenes are characteristically anhedral and interstitial to matrix plagioclase. Their intimate association with tachylite and the arrangement of magnetite and ilmenite inclusions in orderly arrays across glass-pyroxene

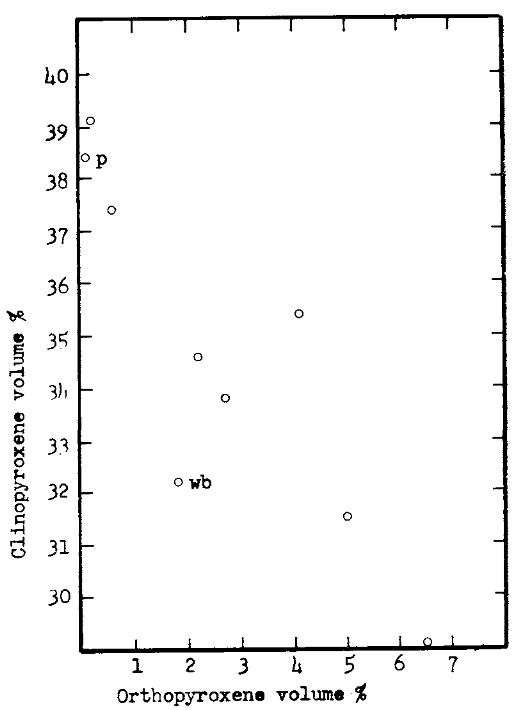

FIG. 4. Modal volumes of pyroxenes in Kaau rift intrusives, *p*, Palolo Quarry pegmatite; *wb*, dense interior of Waialaenui bud.

boundaries establishes the separation of clinopyroxenes to the very end of the groundmass crystallization period. Apparently pyroxene, labradorite, and ores continued to form together until the remaining melt congealed to glass. Minute crystallites of pyroxene and ore dust can be seen in this glass under high magnification.

Feldspar-Magnetite Relationships

The antipathy between feldspar and magnetite in these rocks is worthy of further comment. Formation of magnetite in the intratelluric stage is suggested by well-formed octahedrons occurring as inclusions in olivine and, rarely, in orthopyroxene phenocrysts. Most of the magnetite formed in the groundmass period alongside plagioclase laths, but was not included in them. In view of the greater crystallizing force of magnetite as compared with plagioclase, it seems that the latter could not effectively restrain growth of the magnetite structure. Pyroxenes, which do host abundant matrix magnetite in these rocks, have substantially greater crystallizing force than plagioclase. Evidently factors other than lattice strength are decisive.

Possibly, formation of magnetite was not continuous in these intrusives; but plagioclase crystallization encompasses such a wide interval that contemporaneous separation must have occurred. Contemporaneity is not necessary to make magnetite available for inclusion in feldspar, however. Earlier-formed magnetite could easily be included in later-formed plagioclase. This is undoubtedly the manner of inclusion of magnetite in olivine phenocrysts in these rocks. If olivine formed by epitaxis on early magnetite, the latter might be thus denied to early plagioclase phenocrysts; but when more than one such inclusion appears in optically continuous olivine this mechanism seems doubtful. The coalescence of several olivine crystals into optically homogeneous aggregation is unlikely.

If, as Vogt (1921:321) suggests (in an altogether different chemical environment), the magnetites cluster themselves by synneusis, this glomerocryst might serve as a crystallization nucleus for early olivine. The magnetite inclusions in olivine phenocrysts of these rocks are not typically contact clustered, but they are distinctly localized. Such a mechanism can account only for the absence of magnetite in the larger phenocrysts of plagioclase. The inhospitality of matrix feldspars remains unexplained. Apparently some unique magnetite-plagioclase antipathy is acting here. In other rocks feldspar commonly includes ores, though they tend to favor pyroxene hosts.

It is suggested that in some of these intrusives a few grains of magnetite formed before olivine began to incorporate iron. Ore formation then ceased because the iron content of the melt was slightly diminished and/or because the established centers of magnetite nucleation were enclosed in the growing olivine phenocrysts. The long, very thin olivine phenocrysts hint that considerably more olivine may have formed at an early stage than has survived emplacement and cooling.

As cooling proceeded, orthopyroxene picked up the iron returned to the melt by olivine resorption. After an indeterminate interval, during which formation of orthopyroxene and plagioclase considerably diminished the liquid phase, the magma was intruded into the dike fissure and cooled rapidly. As other components of the melt were depleted, the iron concentration increased. Much iron was accommodated by clinopyroxenes in the groundmass. Linear arrays of magnetite in these clinopyroxenes might suggest exsolution. But unless striking changes in oxidation potential are postulated in magma at least several hundred feet beneath the shield surface, substantial quantities of ferric iron would have to be admitted into pyroxene structures on this hypothesis. Drickamer, Lewis, and Fung (1969:885) have demonstrated a reversible reduction of ferric iron to the ferrous state with increasing pressure in a variety of substances. They indicate that this transition is temperature-sensitive, but their data do not reach the temperature of a basaltic melt. Until this process has been verified with rock-forming silicates at melt temperatures its applicability here remains speculative. In any case, it is doubtful that exsolution from pyroxenes could account for alignments of magnetite octahedrons that are commonly continuous across pyroxene boundaries into glass. Lattice planes in pyroxene hosts do not seem to control magnetite alignment.

Cumuloporphyry

The phenomenon of cumuloporphyry (Johannsen, 1931:203), though widespread in a great variety of rocks, has been neglected in the petrographic literature. It is sometimes used as a diagnostic property of igneous rocks on the assumption that the aggregates so designated could form only with the freedom of movement available in a melt (Vance and Gilreath, 1967: 529).

The relations between individual crystals in these aggregates cannot be explained as epitaxis. Crystal boundaries may be intimate, but the individuals, whether like or unlike species, show no tendency to grow around or envelop their neighbors. The association is most commonly tangency or slight intergrowth (Fig. 5). Flow patterns in matrix feldspar microlites show that the latter have piled against and streamed around each glomerocryst. Relative movement of these phenocryst clots with respect to the surrounding medium is unmistakable. They have behaved as coherent units, withstanding whatever forces attended this passage of the fluid.

Vance and Gilreath (1967:553) attribute the formation of glomerocrysts to a process (synneusis) dependent upon ". . . episodes of turbulence and their timing with respect to the crystallization sequence. . . ." Vogt (1921:321) observed synneusis in cooling ore melts and metallurgical slag, noting that magnetite and zincblende clusters formed within 30 minutes in an essentially static fluid. Spry (1953:255) commented that velocities of magma movement in dikes are probably too low to generate substantial turbulence unless viscosity is very low due to superheating or unusually high volatile content. He held observable structures in bostonite dikes to indicate essentially laminar flow.

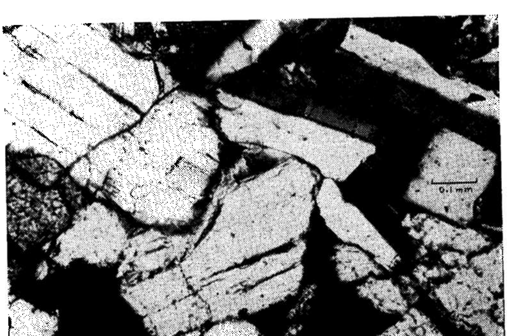

FIG. 5. Intergrowth of plagioclase and orthopyroxene in glomerocryst.

Flow properties in the intrusives of this study are less definitive than those examined by Spry, but the consistent parallelism of microlites in some samples suggests laminar flow. This does not preclude earlier episodes of turbulence at greater depth, however, especially local vortices where the fluid passed an obstruction or irregularity.

Vance and Gilreath also concluded from counting studies that phenocrysts have affinity for their own species and antipathy for unlike species in synneusis. However, Rogers and Bogy (1958:471) found by counting studies in granites that like crystals were *less* likely to form in contact with each other. They contend that this is due to (1) growth of one crystal preventing nucleation of others in the neighborhood, and/or (2) early crystallization of like grains causing them to be isolated from each other by later-forming minerals.

The feldspar and orthopyroxene phenocrysts in this study show a marked tendency toward heterogeneous aggregates, although small single-mineral clusters do rarely appear.

Flow structures in igneous rocks may eventually provide a basis from which to determine rate of magma movement during emplacement. The flow configurations around glomerocrysts observed in this study may have resulted in part from gravity settling of these clusters after magma movement ceased. The mechanism of synneusis remains an open question.

SUMMARY

Exposed dikes and sills trending southwest and roughly perpendicular to the primary rift zone in the Waialae-Palolo area of Oahu are hypersthene-bearing tholeiitic basalts, intrusive equivalents of the basalt lava flows of the Koolau Series. No Honolulu Series intrusives were found along a line joining Kaau Crater, Mauumae, Kaimuki, and Diamond Head, an alleged secondary rift of the Koolau volcano. Bouguer anomaly maps show no indications of substantial intrusive bodies along the southeast Honolulu Series trends, so simple dike feeders are inferred.

The intrusives are typically porphyritic with a fine-grained, hypocrystalline matrix, commonly intersertal in the coarser centers to hyaloophitic at chilled margins. Phenocrysts include olivine, hypersthene, and labradorite. Groundmass minerals are clinopyroxene and labradorite, the former containing abundant ore inclusions. Interstices contain ore-rich tachylite.

The crystallization sequence began with olivine, occasionally preceded by minor magnetite. Orthopyroxene and plagioclase appeared next, in close association, with precedence uncertain. Orthopyroxene separation ceased before groundmass formation, plagioclase continuing to crystallize at increasingly numerous nuclei with clinopyroxene and ores. The remaining fluid finally congealed to dark brown tachylite with ore dust and incipient clinopyroxene crystals.

Modal counts indicate an inverse relation in abundance of clinopyroxene to orthopyroxene, although further data are needed to confirm this. Plagioclase and magnetite are antipathetic throughout these rocks, despite the intimacy of magnetite with all other major species present.

Orthopyroxene and plagioclase are commonly associated in glomerocrysts, which may eventually be useful as a basis to infer flow properties and crystallization sequences in magmas during emplacement.

ACKNOWLEDGMENTS

I wish to thank Dr. G. A. Macdonald for critically reading the manuscript. Field work was supported by a National Science Foundation Research Participation grant during the summer of 1967.

LITERATURE CITED

ADAMS, W. M., and A. S. FURUMOTO. 1965. A seismic refraction study of the Koolau volcanic plug. Pacific Science, vol. 19, pp. 296–305.

BLOSS, F. B. 1961. An introduction to the methods of optical crystallography. New York, Holt, Rinehart and Winston. 294 pp.

CROSS, W. 1915. Lavas of Hawaii and their relations. U. S. Geological Survey, Professional Paper 88, U. S. Government Printing Office, 97 pp.

DRICKAMER, H. G., G. K. LEWIS, Jr., and S. C. FUNG. 1969. The oxidation state of iron at high pressure. Science, vol. 163, pp. 885–890.

GEORGE, W. O. 1924. Composition of glass from refractive index and density. Journal of Geology, vol. 32, pp. 353–372.

HEINRICH, E. W. 1965. Microscopic identification of minerals. New York, McGraw-Hill Book Co. 414 pp.

HITCHCOCK, C. H. 1900. Geology of Oahu. Bulletin of the Geological Society of America, vol. 11, pp. 15–60.

JOHANNSEN, A. 1931. A descriptive petrography of igneous rocks. Vol. I. Chicago, University of Chicago Press. 267 pp.

KUNO, H., and K. NAGASHIMA. 1952. Chemical compositions of hypersthene and pigeonite in equilibrium in magma. American Mineralogist, vol. 37, pp. 1000–1006.

KUNO, H., K. YAMASAKI, C. IIDA, and K. NAGASHIMA. 1957. Differentiation of Hawaiian magmas. Japanese Journal of Geology and Geography, vol. 28, pp. 179–218.

MACDONALD, G. A., and T. KATSURA. 1964. Chemical composition of Hawaiian lavas. Journal of Petrology, vol. 5, pp. 82–133.

ROGERS, J. J. W., and D. B. BOGY. 1958. A study of grain contacts in igneous rocks. Science, vol. 127, pp. 470–471.

SPRY, A. 1953. Flow structure and laminar flow in bostonite dykes at Armidale, New South Wales. Geological Magazine, vol. 90, pp. 248–256.

STEARNS, H. T. 1939. Geologic map and guide of Oahu, Hawaii. Territory of Hawaii, Division of Hydrography Bulletin 2, Pl. 2, 75 pp.

STEARNS, H. T., and K. N. VAKSVIK. 1935. Geology and ground-water resources of the island of Oahu, Hawaii. Territory of Hawaii, Division of Hydrography Bulletin 1, 479 pp.

STRANGE, W. E., L. F. MACHESKY and G. P. WOOLLARD. 1965. A gravity survey of the island of Oahu, Hawaii. Pacific Science, vol. 19, pp. 350–353.

VANCE, J. A., and J. P. GILREATH. 1967. The effect of synneusis on phenocryst distribution patterns in some porphyritic igneous rocks. American Mineralogist, vol. 52, pp. 529–536.

VOGT, J. H. L. 1921. The physical chemistry of the crystallization and magmatic differentiation of igneous rocks. Journal of Geology, vol. 29, pp. 318–350.

WENTWORTH, C. K. 1926. Pyroclastic geology of Oahu. B. P. Bishop Museum Bulletin, vol. 30, pp. 1–121.

WENTWORTH, C. K., and A. E. JONES. 1940. Intrusive rocks of the leeward slope of the Koolau Range, Oahu. Journal of Geology, vol. 48, pp. 975–1006.

WENTWORTH, C. K., and H. WINCHELL. 1947. Koolau basalt series, Oahu, Hawaii. Bulletin of the Geological Society of America, vol. 58, pp. 49–78.

WILLIAMS, H., F. J. TURNER, and C. M. GILBERT. 1954. Petrography: An introduction to the study of rocks in thin sections. San Francisco, W. H. Freeman. 406 pp.

WINCHELL, H. 1947. The Honolulu Series, Oahu, Hawaii. Bulletin of the Geological Society of America, vol. 58, pp. 1–48.

WINCHELL, A. N., and H. WINCHELL. 1937. Elements of optical mineralogy. Part 2. New York, John Wiley & Sons. 551 pp.